

SIMULTANEOUS SEPARATION OF PHOSPHORUS SLUDGE AND MANURE SOLIDS WITH POLYMERS

M. C. Garcia, M. B. Vanotti, A. A. Szogi

ABSTRACT. *In this article, we describe improvement of a manure treatment system without a lagoon through implementation of a concept of simultaneous separation of solids. The original system consisted of three basic processes in series: solid-liquid separation of raw swine manure (SM) using cationic polyacrylamide (PAM), subsequent treatment of liquid through nitrification-denitrification, and a soluble P removal unit. The P removal unit used hydrated lime to precipitate P and anionic PAM to enhance dewatering of the P-rich sludge (PS). Our objectives were to evaluate if it is technically feasible to flocculate and dewater both the PS and SM in a simultaneous operation, using the same dewatering equipment and producing only one stream of solids. The simultaneous separation concept was tested in a laboratory prototype using PS and SM materials from a first-generation version of the system without a lagoon installed in a swine farm in North Carolina. Compared with SM, the PS material had a higher pH (10.1 vs. 7.5), about 5 times more total suspended solids (TSS) (29.5 vs. 5.7 g L⁻¹), and 9 times the total P (2.7 vs. 0.3 g L⁻¹). We found that the PS remained as a solid when mixed with SM, and all the solids were efficiently separated (>90%) using a single polymer application (cationic PAM). The simultaneous separation process did not increase the amount of PAM that would normally be used to effectively treat SM alone. The same dosage of PAM (60 mg L⁻¹) was effective even when the mixture contained 43% more TSS and 94% more TP as a result of PS addition (up to 150 mL L⁻¹). PAM effectiveness in terms of TSS or TP increased with the simultaneous separation process, from 108 to 160 g TSS g⁻¹ PAM, and from 4.7 to 11.4 g TP g⁻¹ PAM. Mass removal efficiencies at the higher PS rate were 96.8% for TSS and 94.7% for TP. The quality of the treated liquid in terms of TSS, COD, and TP concentrations was also improved, and the P content of the separated solids was significantly increased (from 9.5% to 16.9% P₂O₅). Our results indicate that simultaneous separation of two contrasting sludges with PAM is technically feasible, and that the combined separation process is more efficient in terms of polymer use and equipment needs compared with a situation in which two dewatering units are used to separate the same amount of solids. Thus, its implementation can reduce installation and operational cost of the overall treatment system.*

Keywords. *Animal waste, Flocculation, Manure treatment, Nutrient removal, Phosphorus, Polyacrylamide, Polymers, Solid-liquid separation, Swine wastewater.*

A wastewater treatment system was developed to replace the anaerobic swine lagoon technology commonly used in the U.S. to treat swine waste (Vanotti et al., 2005b, 2007). The system met the criteria of an environmentally superior technology (EST) as determined by an agreement between government and swine industry to find technologies that could replace the lagoon system (Williams, 2006). The environmental performance standards of an EST are the following (Williams, 2004): (1) eliminate the discharge of animal waste to surface waters and groundwater through direct discharge, seepage, or run-

off; (2) substantially eliminate atmospheric emissions of ammonia; (3) substantially eliminate the emission of odor that is detectable beyond the boundaries of the swine farm; (4) substantially eliminate the release of disease-transmitting vectors and airborne pathogens; and (5) substantially eliminate nutrient and heavy metal contamination of soil and groundwater. The wastewater treatment system treated the entire waste stream from a swine production unit using three consecutive stages that included solids separation, nitrification/denitrification, and soluble phosphorus removal (Vanotti et al., 2007). As a result, the system cleaned the flushed manure liquid and separated two types of solid materials: manure solids and alkaline calcium phosphate solids. These solid materials were subject to dewatering before leaving the farm. Because of their contrasting characteristics, dewatering was practiced using specific matching polymers and separate equipment. Therefore, we proposed to simplify the design and reduce costs with a simultaneous separation of phosphorus sludge and manure solids using polyacrylamide polymers, which is the goal of the research described in this article.

When polymers are used to enhance solid-liquid separation of sludges (Vanotti and Hunt, 1999; Szogi et al., 2006), the common practice in industry is to match specific polymers to each type of sludge material (WERF, 1993) and then treat each sludge separately. Treatment of industrial and live-

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stock effluents often generates more than one type of sludge in the same plant. Sludges having differing chemical or physical characteristics are typically dewatered using specialized equipment, such as polymer preparation units, pumps, mixing vessels, clarifiers, filters, presses, etc., in order to produce dried solids amenable to transport and/or final disposal. Although the combination of different sludges for the purpose of solid-liquid separation has the potential advantage of eliminating dedicated dewatering equipment and helps reduce the overall cost of treatment, this simultaneous separation concept has not been used in the past.

POLYACRYLAMIDES

Polyacrylamides (PAMs) are moderate to high molecular weight, long-chained, water-soluble organic polymers. The long polymer molecules destabilize suspended, charged particles by adsorbing onto them and building bridges between several suspended particles. With flocculation, the effective particle size is increased by agglomeration of small particles into larger particles, or flocs, that separate from the liquid and dewater more readily. PAMs have varied characteristics, such as molecular weight and charge type (+, 0, -), density distribution of charge (0% to 100%), chain structure, and comonomer, that provide them with a variety of chemical performance characteristics and uses. PAMs are extensively used as a settling agent for food processing and packing, paper production, mine and municipal wastewater treatment, as a clarifier for sugar extraction and potable water treatment, and as a soil conditioner to reduce irrigation water erosion (Barvenik, 1994). It has also been shown that cationic PAMs are also useful to substantially increase separation of suspended solids, organic nutrients, and carbon compounds from liquid animal manures (Vanotti and Hunt, 1999; Chastain et al., 2001; Vanotti et al., 2002; Walker and Kelley, 2003; Timby et al., 2004; Estevez Rodriguez et al., 2005; Vanotti et al., 2007). When this technology is integrated into a liquid manure handling system, it can substantially increase capture of materials that can generate income, such as energy-yielding feedstock and plant growth media (Vanotti et al., 2002). Szogi et al. (2006) used anionic PAM to increase separation of alkaline calcium phosphate extracted from liquid manure. Transport of solids and handling of remaining liquids is made easier, with implications for improved management of nutrients in areas where swine production is concentrated (Vanotti et al., 2002; Estevez Rodriguez et al., 2005).

In this study, we evaluated whether the simultaneous separation of two contrasting sludges using PAM is technically feasible. Our goal was to simplify design and reduce cost of a wastewater treatment system for manure with a simultaneous separation of phosphorus sludge and manure solids using PAM.

MATERIALS AND METHODS

SWINE WASTEWATER TREATMENT SYSTEM WITHOUT LAGOON

The subject of this research was a swine wastewater treatment system without a lagoon (Vanotti et al., 2005b; fig. 1) involving solid-liquid separation, biological N removal, and soluble P removal. It was comprised of (1) a solid separation unit, wherein flocculants were used to clump suspended sol-

ids and increase solid-liquid separation efficiency, (2) a denitrification unit in direct fluid communication with the clarified effluent from the solid separation unit, (3) a nitrification unit in fluid communication with the denitrification unit, (4) a phosphorus separation reactor unit in fluid communication with the liquid effluent from the nitrification unit, and (5) a clarification unit between the nitrification unit and phosphorus unit. Homogenization and storage tanks were added to the system to integrate discontinuous operations, such as flushing and barn pit recharge, with continuous operation of the treatment system (fig. 1a). The treatment system was first pilot tested for two years at North Carolina State University's Lake Wheeler Rd. Swine Unit (Vanotti et al., 2005a). A full-scale version of the system was subsequently constructed on a swine farm in North Carolina for demonstration and EST performance verification (Vanotti et al., 2007; Williams, 2004). In this article, we report laboratory research conducted to support changes in the solids separation, resulting in a second-generation version of the system, to separate and dewater the phosphorus sludge and raw liquid manure in a simultaneous operation, producing only one stream of solids (fig. 1b). In the next two sections, we provide basic information on individual components and functions of the first-generation system, and on the specific improvement that was evaluated in this work.

First-Generation Full-Scale Treatment System

The full-scale demonstration facility was installed on Goshen Ridge farm (unit 1), a 4,360-head swine facility (finishing) near Mount Olive, Duplin County, North Carolina. Manure was collected under the six barns using slatted floors and a pit-recharge system typical of many farms in North Carolina (Barker, 1996). Originally, the production unit used a traditional anaerobic lagoon (0.9 ha) for treatment and storage of manure. As a demonstration project, the production unit was retrofitted with a new waste treatment system (Vanotti et al., 2007) that replaced the lagoon. The new treatment system combined solid-liquid separation with removal of nitrogen (N) and phosphorus (P) from the liquid phase (fig. 1a). It treated an average of 39 m³ per day of liquid manure flushed from the barns. An internal loop recycled N-treated water to refill the barn's pit recharge system (13 m³ d⁻¹). Excess treated water was stored (26 m³ d⁻¹) in the former lagoon and later used for crop irrigation. In addition to a treated liquid stream, the system generated two separated solids streams that left the farm, consisting of manure solids and calcium phosphate solids.

The system was constructed and operated by a private firm, Super Soils Systems USA of Clinton, North Carolina. It was implemented using three process units or modules. The first process unit in the system separated solids from raw flushed manure using PAM polymer flocculant (Vanotti and Hunt, 1999). Before separation, the raw flushed manure was mixed in a homogenization tank. The solid-liquid separation unit used an Ecopurin separation module (Selco MC, Castellon, Spain). It included injection of cationic PAM, reaction in a mixing chamber, and separation of the flocculated manure solids with a stainless-steel wedge-wire rotating screen (250 µm opening size). A small belt filter press (Monobelt, Teknofanghi S.r.l., Milan, Italy) further dewatered the screened solids from a solids content of about 8% to about 18% to 20%. The solid-liquid separation module removed 93% of the total suspended solids contained in the raw ma-

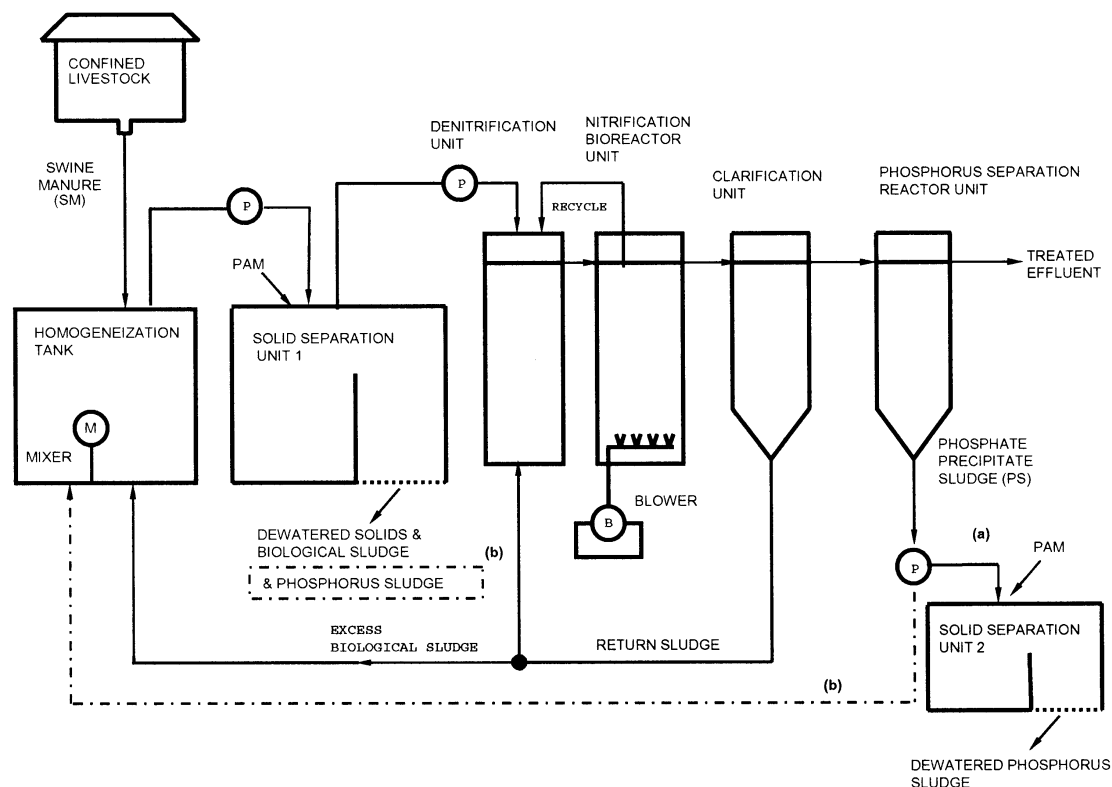


Figure 1. Schematic of the swine manure treatment system without lagoon (Vanotti et al., 2005b): (a) original plant design using two solid separation units demonstrated at full-scale on Goshen Ridge farm, Duplin County, North Carolina; and (b) more economical second-generation design with the proposed separation and dewatering of swine manure and phosphorous sludge using one common solid separation unit.

nure (Vanotti et al., 2007). The separated manure solids were transported offsite to a centralized solids processing facility and converted to organic plant fertilizer, soil amendments, and plant growth media, or used for energy production (Vanotti et al., 2007).

The second process unit in the system used a Biogreen nitrogen removal module (Hitachi Plant Engineering and Construction Co., Tokyo, Japan) to biologically convert ammonia ($\text{NH}_4\text{-N}$) into N_2 gas through nitrification and denitrification. The Biogreen process had a pre-denitrification configuration in which nitrified wastewater was continually recycled to an anoxic denitrification tank (fig. 1a). In this tank, suspended denitrifying bacteria used soluble manure carbon contained in the separated liquid to remove the nitrate. The nitrification tank used nitrifying bacteria immobilized in polymer gel pellets to increase the concentration and effectiveness of the bacterial biomass (Vanotti and Hunt, 2000). The process removed 97% of the NH_3 and substantially reduced bicarbonate alkalinity (88% reduction from liquid containing 4.3 g L^{-1}) (Vanotti et al., 2007). This elimination of ammonia and reduction of carbonate buffering allowed the recovery of P from the liquid using small amounts of lime in the subsequent treatment module (Vanotti et al., 2003).

The third process unit in the system used a soluble P removal module to treat the effluent after biological N treatment (Vanotti et al., 2003). In this module, the P was recovered as calcium phosphate solid (Vanotti et al., 2003), and pathogens were destroyed by the high pH of the process (Vanotti et al., 2005a). Liquid was treated with hydrated lime (30% Ca(OH)_2 slurry) in a stirred reaction chamber. A pH probe and controller linked to the lime injection pump kept the process pH at 10.5 to 11.0. The process removed 94% of

the soluble P from liquid containing 77 to 191 mg L^{-1} (Vanotti et al., 2007). The phosphorus precipitate was decanted in a settling tank. This created a phosphorus sludge (PS) that contained 97% liquid. The PS was removed from the bottom of the tank and dewatered using a Drimad solid-liquid separation unit (Tecnobag-Drimad, Aero-Mod, Inc., Manhattan, Kans.). This separation unit contained 12 filter bags made of non-woven polypropylene fabric (E.I. DuPont de Nemours, Wilmington, Del.) with a $210 \mu\text{m}$ mesh size. Anionic PAM polymer was mixed with the P sludge (PS) to flocculate the fine precipitated solids before entering the filter bags. This flocculation treatment allowed effective capture (>99%) of the P precipitate by the filter bags (Szogi et al., 2006). Bags containing the wet calcium phosphate ($24.4\% \pm 4.5\% \text{ P}_2\text{O}_5$) were removed from the separation unit, dried on a concrete pad, and transported offsite monthly for use as plant fertilizer. For a detailed description and performance evaluation of the full-scale treatment system demonstration, see Vanotti et al. (2007).

Second-Generation Improvement

One possible simplification of the foregoing system is to simultaneously separate and dewater the phosphorus sludge (PS) and liquid swine manure (SM), producing only one solids stream consisting of manure solids enriched with P (fig. 1b). The modification retains all the system's environmental benefits of removing soluble P and pathogens from the final liquid effluent using the P removal module. However, the main advantage of this innovation is the reduction of capital and operational expenses that results from having one solid-liquid separation unit in the treatment plant vs. two solid-liquid separation units (one for SM and another for PS,

fig. 1a). However, characteristics of SM and PS are so different that the type of polymer recommended for solid-liquid separation of each material is also very different. For example, flocculation and separation of SM is optimized with positively charged (cationic) PAM, and neutral or negatively charged (anionic) PAMs are not useful for this application (Vanotti and Hunt, 1999). By contrast, flocculation and separation of alkaline calcium phosphate sludge (PS) is optimized with anionic PAM (Szogi et al., 2006). The objectives of this research were to determine the feasibility and optimize the conditions for the simultaneous separation of SM and PS with PAM.

SWINE MANURE AND PHOSPHORUS SLUDGE SAMPLES

Flushed swine manure (SM) and precipitated phosphorus sludge (PS) used in the laboratory experiments were collected during September and October 2004 from the homogenization tank and the phosphorus separation unit in the full-scale manure treatment plant described above (fig. 1a), with the plant operating at steady-state. The SM samples were collected immediately after flushing manure from three barns into the homogenization tank (about 136 m³). An existing submersible mixer (3.5 kW, 12.1 m³ min⁻¹, ABS Pumps, Inc., Meriden, Conn.) kept the manure well mixed during sampling. The SM samples were taken from mid-height of the homogenization tank using plastic tubing connected to a peristaltic pump sampler (Sigma 900, American Sigma, Inc., Medina, N.Y.) and collected in 20 L plastic containers. The PS samples were taken from the bottom of the settling tank of the phosphate removal unit using existing manual valves and also collected in 20 L plastic containers. The containers were transported in large coolers filled with ice to the USDA-ARS Coastal Plains Research Center in Florence, South Carolina, and kept at 4°C until used in the bench experiments. Characteristics of the SM and PS are summarized in table 1.

BASIC PROCESS CONFIGURATION

The basic configuration of the process studied in all the experiments is shown in figure 2. In this process, phosphorus sludge (PS) containing calcium phosphate is first mixed with swine manure (SM) in a homogenization tank. The mixture is transferred into a polymer mixing vessel, where it is reacted with PAM for flocculation. In the last step, the flocculated solids containing manure and added phosphorus are separated by passing the liquid through a screen.

While the process schematic in figure 2 depicts a continuous operation using separate vessels to mix PS with SM

Table 1. Characteristics of the flushed swine manure and precipitated phosphorus sludge used in the study.^[a]

	Flushed SM	Precipitated PS	PS/SM Ratio
Total suspended solids (g L ⁻¹)	5.72 (1.59)	29.51 (0.14)	5.16
Chemical oxygen demand (g L ⁻¹)	8.41 (1.69)	6.89 (1.07)	0.82
Total phosphorus (mg L ⁻¹)	302 (55)	2741 (92)	9.08
Soluble phosphorus (mg L ⁻¹)	71.6 (8.0)	0.2 (0.2)	0.03
Total Kjeldahl nitrogen (mg L ⁻¹)	942 (176)	251 (52)	0.27
Ammonia-n (mg L ⁻¹)	557 (76)	87 (29)	0.16
pH	7.5 (0.1)	10.1 (0.1)	1.35

^[a] Flushed swine manure (SM) and precipitated phosphorus sludge (PS) used in the bench experiments were obtained from the homogenization tank and phosphorus separation reactor unit (fig. 1a) of the manure treatment plant on a 4400-head swine finishing facility. Data are means (and SD) of nine samples.

(homogenization vessel) and to treat the SM/PS mixture with PAM (polymer mixing vessel), the laboratory tests were performed in a batch mode using a single vessel to perform the same two sequential steps (add PS to SM, mix, add PAM, mix, and then transfer to screen unit).

LABORATORY EXPERIMENTS

We conducted a total of five bench-scale experiments to evaluate the technical feasibility of the simultaneous SM-PS separation process (fig. 2):

1. The first experiment evaluated if the precipitated P in the PS would remain insoluble or re-dissolve when mixed and stirred with SM in a homogenization vessel.
2. The second experiment tested different types of PAMs (cationic, anionic, neutral) to determine which one was most efficient for solid-liquid separation of the SM-PS mixture.
3. The third experiment evaluated if pre-treatment of PS with anionic PAM would enhance the subsequent solid-liquid separation of the SM-PS mixture using cationic PAM.
4. The fourth experiment evaluated if the addition of PS to SM would increase the rate of PAM application compared to the optimum rate needed to treat SM alone without the addition of PS.
5. The last experiment determined the overall PAM separation process performance along with recovery of P in the separated solids when various amounts of PS were added to SM.

Samples of SM and PS collected in the field were transferred into separate 25 L vessels and stirred at 150 rpm with

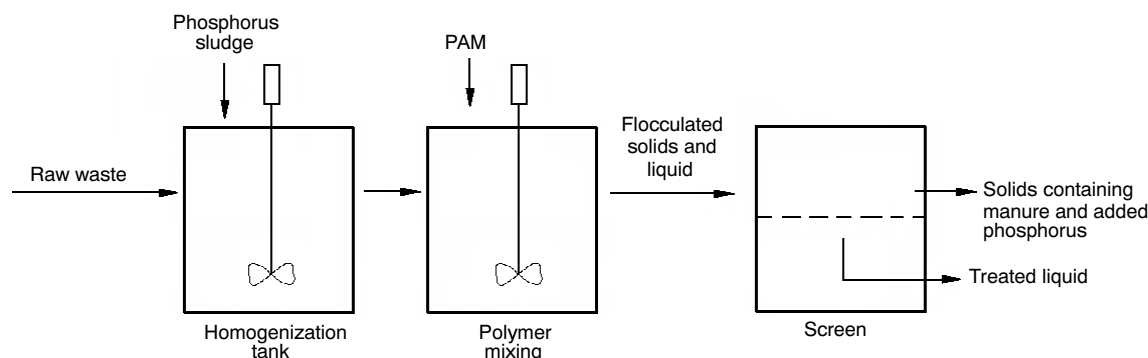


Figure 2. Schematic showing the basic experimental configuration of the process used to simultaneously separate solids from phosphorus sludge and liquid swine manure (raw waste).

a high-torque laboratory mixer fitted with a 7.87 cm diameter A-100 impeller (Labmaster SI, Lightnin Co., Rochester, N.Y.) to obtain homogeneous subsamples or aliquots used for treatment application. The field-collected samples were not combined and were kept separate for each experiment. A peristaltic pump (parts 07553-80 and 07017-21, Cole Parmer Instrument Co., Vernon Hills, Ill.) was used to transfer SM and PS subsamples from the 25 L mixing vessels into smaller glass vessels used to mix the PS and SM, and treat the mixture with PAM. The size of this reaction vessel varied: 1000 mL in experiment 1; 250 mL in experiments 2, 3, and 4; and 50 mL in experiment 5. For screening, disks cut from nylon screen sheets that were mounted on 300 mL funnels were used. The nylon screen had a 250 μm mesh size and 34% opening space (CMN-250-D, Small Parts, Inc., Miami Lakes, Fla.).

Experiments 1 through 4 were done using a SM/PS mixture containing 33 mL of PS per L of SM. This rate considers average flows of 39 $\text{m}^3 \text{d}^{-1}$ for SM into the homogenization tank and 26 $\text{m}^3 \text{d}^{-1}$ for liquid into the P reactor (Vanotti et al., 2007) and a PS generation rate of 50 mL per L treated in the P reactor (Vanotti et al., 2003). In experiment 5, however, we considered other potential uses of the simultaneous separation of SM and PS by using mixtures containing much higher amounts of PS (up to 150 mL PS per L of SM).

The first experiment evaluated the possible re-dissolution of PS when mixed with SM, and for this reason it did not include PAM addition or screening. PS was added to SM at a rate of 33 mL L^{-1} , and the mixture was continuously stirred at 60 rpm during a 24 h period using a 6-unit programmable jar tester (model PB-900, Phipps and Bird, Inc., Richmond, Va.). The experiment was replicated three times and included a replicated control (SM without PS addition). Samples (30 mL) were taken at 0, 0.5, 1, 2, 3, 18, and 24 h from the mixing vessel and analyzed for soluble P and pH.

The second experiment compared the performance of cationic (+), neutral (0), and anionic (−) PAMs for solid-liquid separation of the SM/PS mixtures. The polymers employed were commercially available PAM formulations (table 2). For cationic PAM, two types were evaluated: one with 20% charge density, and another with 75% charge density. The PAM treatments were applied to the SM/PS mixture (33 mL PS per L of SM) using working solutions at a rate of 60 mg active ingredient (a.i.) per liter. Working solutions of PAM were 0.2% secondary solutions after preparation of 0.5% primary stocks (WERF, 1993). The SM/PS and PAM were mixed for 30 s and poured into a 0.25 mm screen to separate the mixture into its solid and liquid (filtrate) components. Treatment performance was determined by the difference between TSS, COD, and TP concentrations in the filtrate and those of the initial SM/PS mixture before PAM application and screening. The experiment was replicated twice and included a control treatment without polymer addition.

Table 2. Characteristics of polyacrylamides (PAMs) used in the study.

Chemical Treatment	Polymer Name ^[a]	Charge Type	Charge Density (mole %)	Active Polymer (%)	Physical Form
PAM-N	Magnifloc 985N	Neutral	0	85	Powder
PAM-A	Magnafloc 120L	Anionic	34	50	Liquid
PAM-C	Magnifloc 494C	Cationic	20	85	Powder
PAM-HC	Excel Ultra 5000	Cationic	75	27	Liquid

^[a] Magnifloc 985N, Magnifloc 494C, and Excel Ultra 5000 supplied by Cytec Industries, Inc., West Paterson, N.J.; Magnafloc 120L supplied by Ciba Specialty Chemicals Water Treatment, Inc., Suffolk, Va.

In the third experiment, the PS was pre-treated with four rates (0, 15, 30, and 60 mg a.i. L^{-1}) of anionic PAM (Magnafloc 120L, table 2) in separate glass vessels before its addition to the SM. The pre-treated PS was mixed with the SM in the homogenization vessel. Subsequently, the SM/PS mixture was treated with cationic PAM (60 mg L^{-1} Magnifloc 494C, table 2) and passed through a screen, as previously described for experiment 2. Treatment effectiveness was determined by assessing the quality of the filtrate (TSS, COD, TP, soluble P, TKN, and $\text{NH}_4\text{-N}$) compared to initial concentrations. The control was a single polymer application of 0 mg L^{-1} of PAM-A and 60 mg L^{-1} PAM-C. The experiment was replicated two times.

The fourth experiment was a paired PAM rate study performed on SM alone and on SM/PS mixtures. SM was added to ten glass reaction vessels, but only half received additional PS treatment (33 mL L^{-1}). Five PAM rates (0, 30, 60, 90, and 120 mg a.i. L^{-1}) were then applied to each group. Cationic PAM with 20% charge density was used (Magnifloc 494C, table 2). Polymer application and subsequent screening were performed as previously described for experiment 2. Flocculation and filtration performance were determined by assessing the quality of the liquid filtrate, which included TSS, COD, TP, and soluble P determinations. The experiment was performed on three different SM field samples of various strengths, and it was replicated two times.

The last experiment used seven PS rate treatments in order to assess P recovery after simultaneous flocculation with SM using PAM. We also determined P content of the separated solids obtained in the process. PS treatment rates were 0, 15, 30, 60, 90, 120, and 150 mL per L of SM. The PAM used was cationic with 20% charge density (Magnifloc 494C, table 2). It was applied at the same rate (60 mg L^{-1}) to every SM/PS mixture treatment combination. Polymer application and screening were performed as previously described for experiment 2. In addition to the water quality of the filtrate (TSS, COD, TP, soluble P, TKN, alkalinity, and pH), we assessed the dry weight and chemical composition (TP and TKN) of the solids separated by the screen. The same PS treatments were applied to three different field samples and replicated two times. A control treatment consisting of screened SM without PS or PAM addition was also included as a reference point.

ANALYTICAL METHODS

Wastewater and phosphorus sludge analyses consisted of total suspended solids (TSS), chemical oxygen demand (COD), total Kjeldahl N (TKN), total P (TP), soluble P (*o*- PO_4), ammonia-N ($\text{NH}_4\text{-N}$), pH, and alkalinity. All the analyses were done according to *Standard Methods for the Examination of Water and Wastewater* (APHA, 1998). Total suspended solids (TSS) were determined from the solids retained on a 1.5 μm glass-fiber filter (Whatman grade 934-AH, Whatman, Inc., Clifton, N.J.) and dried at 105°C (Standard Method 2540 D). Chemical oxygen demand (COD) was measured with the closed reflux, colorimetric method (Standard Method 5220 D). Soluble P was determined by the automated ascorbic acid method (Standard Method 4500-P F) after filtration through a 0.45 micron membrane filter (Gelman type Supor-450, Pall Corp., Ann Arbor, Mich.). The same filtrate was used to measure $\text{NH}_4\text{-N}$ by the automated phenate method (Standard Method 4500-NH₃ G). Total P and TKN were determined using the

ascorbic acid method and the phenate method, respectively, adapted to digested extracts (Technicon, 1977). Alkalinity was determined by acid titration to the bromocresol green endpoint (pH = 4.5) and expressed as mg CaCO₃ L⁻¹.

Separated solids collected after screening were dried at 45 °C in a forced-air chamber and analyzed for TP and TKN using the acid block digestion procedure of Gallaher et al. (1976) and the colorimetric methods described above. Treatment performance was determined by the difference between TSS, TP, and COD concentrations in the treated liquid and those in the initial mixture before PAM application and screening. Phosphorus recovery in the solids was determined using mass balances that considered solids weight and P concentration. Data were statistically analyzed by means and standard deviations (proc MEANS), analyses of variance (proc ANOVA), and least significant difference (LSD) tests at the 5% level for significant differences among treatment means (SAS, 1988). Linear regression analysis was used to describe P recovery in solids as related to P added to swine manure with the phosphorus sludge.

RESULTS AND DISCUSSION

RE-DISSOLUTION OF PHOSPHORUS SLUDGE IN THE SWINE MANURE MIXTURE

One critical assumption for the successful implementation of the process of simultaneous solid-liquid separation of PS and SM is that the calcium phosphate precipitate (generated at pH > 10.5) does not re-dissolve when PS is mixed with SM (pH ~ 7.5) in the homogenization vessel (fig. 2). This assumption is important because subsequent PAM application in this process is to agglomerate suspended solid particles in the mixed liquor. PAM is not effective for removal of soluble P contained in liquid swine manure (Vanotti and Hunt, 1999). The PS non-redissolution assumption was confirmed by assessing levels of soluble P in the SM/PS mixture during a 24 h mixing period and comparing results with those of a control consisting of stirred SM without PS addition (table 3). In this initial experiment, PS containing 3143 mg TP L⁻¹ and <1 mg soluble P L⁻¹ was added to SM at a rate of 33 mL L⁻¹. In a situation of complete re-dissolution, this PS addition would have increased soluble P concentration in the mixture by 104 mg L⁻¹. Instead, results showed that soluble P concentrations in the SM/PS mixture were significantly decreased by about half relative to SM (table 3). This decrease occurred instantly once the PS was in contact with the SM (time = 0 h), and it was maintained throughout the 24 h stirring period (table 3). Two conclusions are derived from this finding: (1) calcium phosphate precipitate generated with the soluble P removal process (Vanotti et al., 2003, 2005b) does not re-dissolve when mixed with SM; therefore, it is amenable for simultaneous separation with flocculants; and (2) its addition to raw SM can remove additional soluble P from the liquid phase. A possible explanation for this additional removal is due to adsorption of P to excess calcium ions in the alkaline precipitate.

A second critical assumption for the successful implementation of the process of simultaneous solid-liquid separation of SM and PS is that the alkaline PS addition does not result in a significant pH increase of the mixed liquor. This is important because high pH (>9) promotes conversion of NH₄⁺ into NH₃ and gaseous N emissions, which are contrary

Table 3. Evaluation of re-dissolution of phosphorus precipitate in the homogenization vessel by measuring changes in soluble P and pH after its addition and mixing with liquid swine manure.^[a]

Time (h)	Mixed Liquor pH		Mixed Liquor Soluble P (mg L ⁻¹)	
	Without PS	With PS ^[b]	Without PS	With PS
0	7.6 (0.02)	7.7 (0.02)	65.9 (4.1)	33.8 (4.6)
0.5	7.7 (0.05)	7.8 (0.04)	65.2 (1.0)	36.8 (2.7)
1	7.7 (0.01)	7.8 (0.02)	63.3 (3.9)	36.3 (1.1)
2	7.8 (0.01)	7.9 (0.01)	62.1 (7.5)	38.4 (1.2)
3	7.9 (0.01)	7.9 (0.03)	65.7 (1.7)	42.7 (3.8)
18	8.4 (0.01)	8.4 (0.01)	53.1 (1.4)	32.4 (0.9)
24	8.4 (0.02)	8.4 (0.03)	50.8 (0.7)	28.9 (0.8)

^[a] This experiment (exp. 1) evaluated changes in soluble P and pH in the mixture of flushed swine manure and precipitated phosphorus sludge (PS) during mixing in the homogenization vessel (fig. 2) without any addition of PAM. A control consisting of swine manure without PS addition is also included. Data are means (and SD) of three replicates.

^[b] PS was added at a rate of 33 mL per L of flushed swine manure. Characteristics of swine manure (before mixing) were: pH = 7.53, TP = 342 mg L⁻¹, and soluble P = 66 mg L⁻¹. Characteristics of precipitated phosphorus sludge were: pH = 10.24, TP = 3143 mg L⁻¹, and soluble P = 0.8 mg L⁻¹.

to the function of the total system we were trying to improve (fig. 1). Fortunately, liquid swine manure has a high buffer capacity (Fordham and Schwertmann, 1977; Sommer and Husted, 1995), which makes difficult to increase its pH with alkali additions (Vanotti et al., 2003). Results obtained in the 24 h mixing experiment (table 3) showed that pH of the mixed liquor was not significantly increased ($p > 0.05$) with the addition of alkaline PS compared to a control without PS addition (table 3). Although pH increased 0.9 units after the 24 h stirring period, this increase was similar for both treatments (with and without PS addition). Thus, it was unrelated to the PS addition. Most likely, it was related to aeration of the SM caused by continuous stirring because experiments on aeration of anaerobic SM (Vanotti and Hunt, 2000; Zhu et al., 2001) have shown similar pH increases (about 1 unit) during the first day of aeration treatment.

PAM TYPE EVALUATION

A third critical assumption for the successful implementation of the process of simultaneous solid-liquid separation of SM and PS is that there is at least one PAM treatment that can simultaneously affect both solids in the mixture. The effect of PAM charge type and density on TSS, COD, and TP separation from a mixture of SM and PS is shown in table 4. In this experiment (experiment 2), the SM/PS mixture (33 mL PS per L of SM) was treated with various PAMs (table 2) having different charge types (anionic, neutral, and cationic) and density (within the cationic group) using a uniform rate of 60 mg L⁻¹. Data presented in table 4 show characteristics of the treated liquid after screening (0.25 mm opening size) and include a control treatment without PAM addition (screening only). Without PAM addition, the effluent was turbid (4030 mg TSS L⁻¹), resulting in low (<38%) separation efficiencies for TSS, COD, and TP with respect to the initial SM/PS mixture. Polymer type was very important for the overall effectiveness of the simultaneous solid-liquid separation process evaluated. Both anionic and highly charged cationic PAMs (PAM-A and PAM-HC, table 4) were not useful for this application: PAM-A showed an overall poor performance not different from that of the control, and PAM-HC was effective

Table 4. Effect of polyacrylamide (PAM) charge type on separation of TSS, COD, and TP from a mixture of flushed swine manure and precipitated P sludge using polymer flocculation and screening.^[a]

Chemical Treatment ^[b]	TSS		COD		TP	
	Effluent Conc. (g L ⁻¹)	Removal Efficiency ^[c] (%)	Effluent Conc. (g L ⁻¹)	Removal Efficiency (%)	Effluent Conc. (mg L ⁻¹)	Removal Efficiency (%)
Control	4.03 (1.79)	38.0	6.01 (1.59)	27.4	244 (73)	36.6
PAM-N	1.32 (0.14)	79.7	2.61 (0.38)	68.5	74 (0.4)	80.7
PAM-A	3.71 (1.43)	42.9	5.82 (1.53)	29.7	218 (74)	43.2
PAM-C	0.24 (0.02)	96.3	2.09 (0.04)	74.8	65 (5)	83.1
PAM-HC	0.77 (0.33)	88.2	2.86 (0.11)	65.5	337 (11)	12.1

[a] Experimental configuration is shown in figure 2. In this experiment (exp. 2), the mixture of flushed swine manure (SM) and precipitated P sludge (PS) was treated with various PAMs with different charge types. Data show characteristics of the treated liquid after screening. Data are means (and SD) of two replicates.

[b] Control = screened effluent without PAM addition. PAM rate = 60 mg active polymer L⁻¹; N = neutral, A = anionic, C = cationic with 20% charge density, HC = cationic with 75% charge density (table 2).

[c] Removal efficiency relative to concentrations in the mixture of SM and PS (homogenization, fig. 2). Mixture contained 6.50 g TSS L⁻¹, 8.28 g COD L⁻¹, and 384 mg TP L⁻¹; P sludge contributed 16%, 4%, and 22% of the TSS, COD, and TP in the mixture, respectively.

in capturing manure solids (88%) but interacted negatively with the PS, resulting in a low TP removal efficiency (12%) that was worse than the control. In contrast, neutral and moderately charged cationic PAMs (PAM-N and PAM-C, table 4) showed a superior performance that was consistent among water quality indicators evaluated, with PAM-C having the highest and most desirable removal efficiencies for TSS (96%), COD (75%), and TP (83%). Therefore, cationic PAM with 20 mole % charge density (PAM-C) was selected for use in subsequent experiments. The reaction of PAM-C and the SM/PS mixture was instantaneous and produced large, dark brown flocs with white calcium phosphate particles enmeshed within the flocs. In turn, the flocs containing both SM and PS solids were readily separated with the screen, leaving a remarkably clear (TSS = 240 mg L⁻¹) liquid effluent (table 4). We therefore conclude that it is technically feasible to simultaneously separate a mixture of SM and PS through PAM flocculation and dewatering.

These results confirm the general premise that cationic polymers would be more useful for treating animal wastewater because organic particles suspended in neutral and alkaline wastewaters generally have a negative charge. The best polymer type identified for the simultaneous SM/PS separation treatment is in agreement with the findings of Vanotti and Hunt (1999) for solid-liquid separation of SM. They found that cationic PAMs with moderate charge density (20 to 35 mole %) are more effective than cationic PAMs with higher charge density (40 to 75 mole %), and that anionic types are not useful for this application. Other results were plausi-

ble; adsorption of anionic PAM on negatively charged particles is also common (Stumm and O'Melia, 1968; Lentz et al., 1993; Szogi et al., 2006).

Of special interest to this study was the work of Szogi et al. (2006), who found that flocculation and screen separation of alkaline calcium phosphate sludge (PS) is optimized with anionic PAMs (10 to 34 mole % charge density). For this reason, an additional polymer type experiment (experiment 3) was conducted to evaluate if a pre-treatment of PS with anionic PAM (before its addition to SM) further improves the separation efficiency of the SM/PS mixture using cationic PAM (table 5). The process thus evaluated involved an additional first step in which the PS was treated (flocculated) with PAM-A (at 15, 30, and 60 mg L⁻¹ rates). Subsequently, the flocculated PS was mixed with SM in a homogenization vessel, treated with PAM-C (60 mg L⁻¹), and screened as described before. The control in this experiment was a single polymer application (0 mg L⁻¹ of PAM-A and 60 mg L⁻¹ PAM-C, table 5). Results showed that pre-treatment of the PS with moderate amounts (15 to 30 mg L⁻¹) of anionic PAM did not improve efficiency of cationic PAM compared to the control, and that higher amounts (60 mg L⁻¹) of anionic PAM reduced the effluent quality (table 5). The single polymer application (control) removed 96% of TSS, 68% of COD, 83% of TP, and 35% of TKN from the SM/PS mixture.

From the preceding experiments, we conclude that the use of a single polymer (cationic PAM) applied to the homogenized SM/PS is the best option for simultaneous solid-liquid separation of SM and PS. The implications of these findings

Table 5. Removal of solids, COD, phosphorus, and nitrogen from a mixture of flushed swine manure and precipitated P sludge by PAM flocculation and screening.^[a]

Anionic PAM Applied to P Sludge ^[b] (mg L ⁻¹)	Cationic PAM Rate ^[c] (mg L ⁻¹)	Water Quality Characteristics of Treated Liquid ^[d]					
		TSS (g L ⁻¹)	COD (g L ⁻¹)	TP (mg L ⁻¹)	Soluble P (mg L ⁻¹)	TKN (mg L ⁻¹)	NH ₄ -N (mg L ⁻¹)
0	60	0.23 (0.06)	2.66 (0.96)	66.4 (8.8)	32.4 (0.2)	542 (11)	431 (4)
15	60	0.31 (0.07)	2.30 (0.08)	66.6 (2.6)	32.3 (5.5)	544 (19)	446 (0.6)
30	60	0.32 (0.12)	1.98 (0.48)	66.6 (6.0)	33.9 (0.6)	543 (12)	450 (12)
60	60	0.44 (0.08)	2.45 (0.53)	78.8 (10.6)	40.7 (2.7)	582 (27)	462 (2)

[a] Experimental configuration is shown in figure 2. In this experiment (exp. 3), the phosphorus sludge (PS) was pre-treated (flocculated) with varied amounts of anionic PAM before its addition to the homogenization vessel and mixing with flushed swine manure (SM). Subsequently, the mixture was treated with cationic PAM and screened. Data show characteristics of the treated liquid (after flocculation and screening).

[b] Anionic PAM = Magnifloc 120L (table 2). Rates are mg active polymer L⁻¹ PS.

[c] Cationic PAM = Magnifloc 494C (table 2). Rates are mg active polymer L⁻¹ SM-PS mixture.

[d] Data are means (and SD) of two replicates. Based on concentrations in SM and PS, and amount of PS added (33 mg L⁻¹), the initial mixture should contain 6.50 g TSS L⁻¹, 8.28 g COD L⁻¹, 383.5 mg TP L⁻¹, 54.6 mg soluble P L⁻¹, 840 mg TKN L⁻¹, and 445 mg NH₄-N L⁻¹. PS contributed 16% TSS, 4% COD, 22% TP, <0.1% soluble P, 1% TKN, and 0.1% NH₄-N to the mixture.

are important for system development. In the first-generation system (fig. 1a), anionic PAM application was used to flocculate PS and allow effective separation of the calcium phosphate precipitate using specialized filtration dewatering equipment. Results obtained in experiments 2 and 3 (tables 4 and 5) indicate that this flocculation step would not be needed in the second-generation system (fig. 1b) because the same PAM type that optimizes SM separation also optimizes separation of solids from the SM/PS mixture. Therefore, the simultaneous SM/PS separation process has the dual advantages of using one common dewatering unit for both SM and PS and eliminating previous equipment and operational expenses associated with the use of anionic PAM to condition the PS for effective dewatering.

OPTIMUM RATE OF PAM APPLICATION

The rate of PAM application to the mixture of SM and PS was compared to the optimum rate needed to treat SM alone without the addition of PS (table 6). In this experiment (experiment 4), six PAM rates (0 to 120 mg L⁻¹) were applied to an SM/PS mixture (containing 3.3% PS), and its treatment performance was compared to a situation in which the same PAM rates were applied to SM without PS to evaluate if the PS addition resulted in a significantly higher PAM dose requirement. Results showed that the addition of PS to the SM did not increase the amount of PAM that would normally be used to effectively treat SM (table 6). PAM application rates ≥ 60 mg L⁻¹ to the SM/PS mixture and to SM alone produced consistently produced high separation efficiencies for TSS and COD ($>90\%$ and $>70\%$, respectively, table 6). In both cases, the screened effluent after PAM application was clarified and contained relatively low TSS (0.21 to 0.38 mg L⁻¹) compared to the turbid effluent obtained without PAM treatment (2.75 to 3.16 mg TSS L⁻¹) or to initial levels in the homogenization vessels (3.93 to 4.40 mg TSS L⁻¹). At equal PAM application rates, however, removal efficiencies for TP were higher for the SM/PS mixture compared to SM alone (78% to 80% vs. 60% to 64%, respectively). This higher TP

removal efficiency for the SM/PS mixture was due in part to higher amounts of particulate P present (212 vs. 145 mg L⁻¹; particulate P = TP – soluble P), which is amenable for solid-liquid separation, and in part because of additional capture of soluble P (about 30%) by the added PS, a fraction that is typically not separated with PAM treatment alone (table 6).

Flocs produced from application of PAM to SM/PS separated from the screen more easily because they were not as sticky as the flocs produced when PAM was applied to SM alone. This self-cleaning action represents a significant advantage of the simultaneous separation process because solid-liquid separation of manure using PAM and screening requires frequent washing of the screen surface in order to keep it unclogged and functional.

WATER QUALITY CHARACTERISTICS OF THE TREATED EFFLUENT

Data in table 7 and figure 3 show that water quality of the treated liquid in terms of TSS, COD, TP, and TKN concentrations was actually improved when increased amounts of PS were added to SM (up to 15% or 150 mL L⁻¹ evaluated). The same dosage of PAM (60 mg L⁻¹) was effective in separating solids for all six SM/PS mixtures, even when PS addition increased TSS concentration by 43% (from 6.93 to 9.93 g L⁻¹, fig. 3) and TP concentration by 94% (from 373 to 723 mg L⁻¹, fig. 3). Removal efficiencies obtained at the higher PS rate (150 mL L⁻¹) were 96.8% for TSS, 94.7% for TP, 85.4% for COD, 61.5% for soluble P, 39.5% for TKN, and 64.8% for alkalinity. The corresponding PAM use efficiencies for TSS (g TSS removed g⁻¹ PAM) increased linearly, from 108 to 160 g TSS g⁻¹ PAM, with increased amount of PS added to SM in the range 0 to 150 mL L⁻¹. Polymer use efficiencies were also calculated in terms of TP (g TP separated g⁻¹ PAM). These efficiencies also increased linearly with the PS addition, from 4.7 to 11.4 g TP g⁻¹ PAM (fig. 4). These results indicate that the simultaneous separation process is much more efficient in terms of polymer consumption compared with a situation in which two dewatering units are used to separate the same amount of solids.

Table 6. Removal of total suspended solids (TSS), chemical oxygen demand (COD), total phosphorus (TP), and soluble P from flushed swine manure or a mixture of manure and precipitated phosphorus sludge by PAM flocculation and screening.^[a]

Cationic PAM Rate (mg L ⁻¹)	TSS		COD		TP		Soluble P	
	Effluent Conc. (g L ⁻¹)	Removal Efficiency ^[b] (%)	Effluent Conc. (g L ⁻¹)	Removal Efficiency (%)	Effluent Conc. (mg L ⁻¹)	Removal Efficiency (%)	Effluent Conc. (mg L ⁻¹)	Removal Efficiency (%)
Treatment of Flushed Swine Manure without Phosphorus Sludge Addition								
0	2.75 (1.91)	30.0	5.02 (3.10)	27.6	189 (142)	13.8	75.8 (7.4)	0
30	0.51 (0.02)	87.0	2.53 (0.62)	63.5	152 (127)	30.6	72.9 (11.5)	1.7
60	0.37 (0.07)	90.6	1.94 (0.84)	72.0	87 (12)	60.5	76.4 (8.9)	0
90	0.31 (0.16)	92.1	1.68 (0.71)	75.8	80 (14)	63.3	76.7 (14.8)	0
120	0.21 (0.09)	94.7	1.46 (0.53)	78.9	79 (16)	64.2	76.5 (14.2)	0
Treatment of a Mixture of Flushed Swine Manure and Phosphorus Sludge								
0	3.16 (2.04)	32.8	5.38 (2.72)	22.1	222 (132)	21.9	45.1 (10.9)	37.1
30	0.54 (0.08)	88.5	2.09 (0.55)	69.8	128 (108)	55.0	50.8 (6.2)	39.2
60	0.38 (0.07)	91.9	1.63 (0.61)	76.4	62 (14)	78.4	51.0 (6.6)	28.9
90	0.23 (0.09)	95.1	1.43 (0.63)	79.3	59 (10)	79.3	52.3 (8.9)	27.1
120	0.24 (0.10)	94.9	1.40 (0.58)	79.7	56 (14)	80.3	52.4 (9.5)	27.0

^[a] Experimental configuration is shown in figure 2. In this experiment (exp. 4), various rates of cationic PAM (Magnifloc 494C, table 2) were applied to swine manure or to a mixture of swine manure and precipitated P sludge. Data show characteristics of the treated liquid after screening. Data are means (and SD) of two replicate tests performed on three field samples ($n = 6$).

^[b] Removal efficiency relative to concentrations in the homogenization vessel before PAM treatment (fig. 2). Concentrations in swine manure were: TSS = 3.93 g L⁻¹, COD = 6.93 g L⁻¹, TP = 219 mg L⁻¹, and soluble P = 74.1 mg L⁻¹. Concentrations in P sludge were: TSS = 27.9 g L⁻¹, COD = 6.10 g L⁻¹, TP = 2254 mg L⁻¹, and soluble P = 0.1 mg L⁻¹. P sludge was added at a rate of 33 mL L⁻¹, which resulted in a mixture with 4.40 g TSS L⁻¹, 6.91 g COD L⁻¹, 284 mg TP L⁻¹, and 71.8 mg soluble P L⁻¹.

Table 7. Water quality characteristics of the treated liquid using simultaneous separation of solids from liquid swine manure and precipitated P sludge.^[a]

P Sludge Added to Swine Manure ^[b]		Water Quality Characteristics of Treated Liquid ^[c]						
(mL L ⁻¹)	% (v v ⁻¹)	TSS (g L ⁻¹)	COD (g L ⁻¹)	TP (mg L ⁻¹)	Soluble P (mg L ⁻¹)	TKN (mg L ⁻¹)	Alkalinity (g L ⁻¹)	pH
No PAM applied (screening only)								
0	0	4.84 (1.17)	7.33 (2.32)	266.3 (58.8)	74.8 (6.5)	1,001 (200)	4.43 (0.11)	7.82 (0.15)
60 mg L ⁻¹ of cationic PAM applied to mixture ^[d]								
0	0	0.45 (0.24)	2.09 (0.83)	91.7 (14.3)	69.4 (3.7)	638 (162)	3.20 (0.60)	7.85 (0.15)
15	1.5	0.42 (0.21)	2.08 (1.16)	74.1 (24.9)	55.3 (2.7)	621 (184)	2.93 (0.43)	7.90 (0.21)
30	3	0.39 (0.24)	1.94 (0.85)	68.4 (14.4)	47.1 (3.4)	623 (162)	2.89 (0.50)	7.92 (0.18)
60	6	0.38 (0.13)	1.16 (0.06)	54.2 (4.1)	33.8 (5.4)	608 (118)	2.97 (0.48)	7.97 (0.17)
90	9	0.36 (0.08)	1.09 (0.09)	36.8 (10.9)	25.0 (5.9)	546 (183)	2.78 (0.36)	8.00 (0.18)
120	12	0.39 (0.03)	1.36 (0.47)	37.6 (6.1)	17.7 (7.4)	544 (148)	2.63 (0.55)	8.07 (0.16)
150	15	0.32 (0.08)	1.33 (0.56)	38.3 (10.8)	15.2 (5.9)	554 (110)	2.66 (0.49)	8.11 (0.14)

- [a] Experimental configuration is shown in figure 2. In this experiment (exp. 5), increased amounts of phosphorus sludge were added to the homogenization vessel and mixed with flushed swine manure. Subsequently, the various mixtures were treated with cationic PAM and screened. Data show characteristics of the treated liquid after flocculation and screening. The separated solids were also analyzed for phosphorus content and mass recovery (table 8).
- [b] Characteristics of the raw swine manure were: TSS = 6.91 g L⁻¹, COD = 9.11 g L⁻¹, TP = 367 mg L⁻¹, soluble P = 71.8 mg L⁻¹, TKN = 1030 mg L⁻¹, alkalinity = 4.42 g L⁻¹, and pH = 7.43. Characteristics of the P sludge were: TSS = 29.9 g L⁻¹, COD = 6.37 g L⁻¹, TP = 3058 mg L⁻¹, soluble P = 0.3 mg L⁻¹, TKN = 200 mg L⁻¹, alkalinity = 8.10 g L⁻¹, and pH = 10.1.
- [c] Data are means (and SD) of two replicate tests performed on three field samples ($n = 6$). LSD_{0.05} values to compare means within a column are: TSS = 0.16, COD = 533, TP = 11.3, soluble P = 5.18, TKN = 38, alkalinity = 0.34, and pH = 0.29.
- [d] Cationic PAM = Magnifloc 494C (table 2).

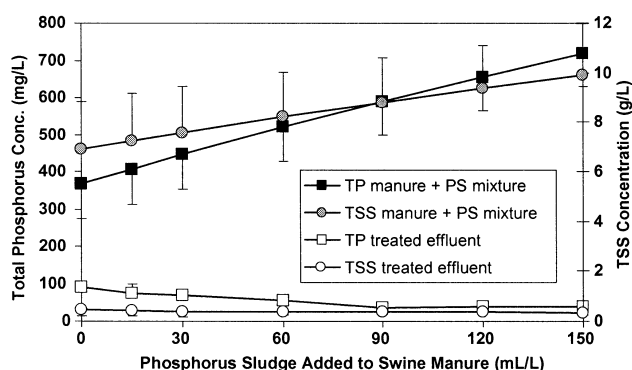


Figure 3. Removal of total phosphorus (TP) and total suspended solids (TSS) from mixtures of liquid swine manure and precipitated P sludge (PS) using PAM flocculation and screening. Each point is the average of six tests. Complete analyses of the treated effluent are shown in table 7.

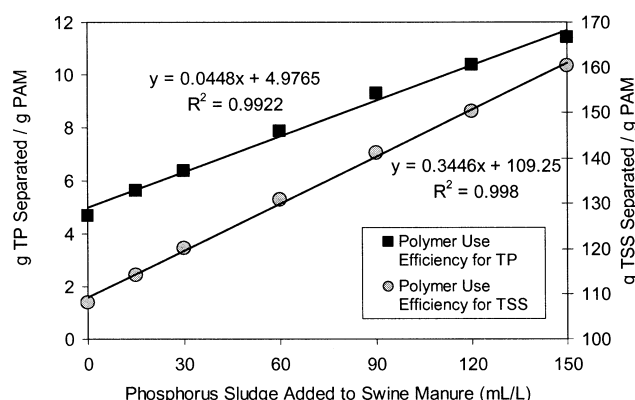


Figure 4. Polymer use efficiency obtained with increased amount of PS added to SM. Polymer use efficiencies were calculated with respect to TP and TSS removals using data in figure 3.

The pH and alkalinity are important considerations for optimum biological N treatment. If the wastewater contains insufficient alkalinity, then growth of the autotrophic biomass will cease because the inorganic carbon needed by the microorganism is missing, and because of the acid pH (Grady et al., 1999; Vanotti and Hunt, 2000). The pH and alkalinity characteristics of the liquid after the simultaneous separation process were within values considered optimum for biological N treatment of liquid swine manure. The pH increased slightly from 7.9 to 8.1 after addition of 150 mL L⁻¹ of alkaline PS, which illustrates the high buffer capacity of the SM (table 7). The effluent pH obtained from the various SM/PS mixtures were within a reported pH range of 7.7 to 8.5, which optimizes nitrification treatment of SM (Vanotti and Hunt, 2000). The alkalinity concentration in the treated liquid was sufficient for complete biological N removal treatment using the nitrification/denitrification configuration shown in figure 2. For example, the alkalinity concentration of 2.66 g L⁻¹ obtained at the higher PS rate (table 7) was higher than the minimum alkalinity requirement of 1.98 g L⁻¹ needed for nitrification/denitrification of liquid containing 554 mg N L⁻¹ (table 7). This requirement considers an alkalinity consumption of 3.57 mg CaCO₃ per mg N converted to N₂, i.e., release of 2 moles of H⁺ per mole of NH₄⁺ oxidized, and consumption of 1 mole of H⁺ per mole of NO₃⁻ reduced (Tchobanoglous and Burton, 1991).

PHOSPHORUS RECOVERY IN THE SEPARATED SOLIDS

More than 90% of the total P removed from the SM/PS liquid mixture was recovered in the separated solids, as shown in the solids analyses (table 8). These calculations include the original P in manure (373 mg L⁻¹) and P added with the PS (up to 458.6 mg L⁻¹ manure). When one considers only the incremental P recovery in the solids (above that originally contained in the manure), the simultaneous separation process produced a quantitative recovery of the P in the PS that was added to the SM (fig. 5).

Table 8. Phosphorus content and recovery in solids produced from mixtures of liquid swine manure and phosphorus sludge using a simultaneous separation process.^[a]

P Sludge Added to Swine Manure		Total P Added To Swine Manure (mg L ⁻¹)	Total P in the Homogenization Vessel (1) (mg)	Total P Recovered in the Separated Solids (2) (mg)	Total P Recovery [(2/1) × 100] (%)	P Content of Solids (% P ₂ O ₅)
(mL L ⁻¹)	% (v v ⁻¹)					
0	0	0	373.0 (96.1)	268.8 (81.5)	71.7 (9.5)	9.5 (0.5)
15	1.5	45.8 (1.2)	418.9 (96.9)	381.5 (112.6)	90.2 (7.2)	11.4 (1.6)
30	3	91.8 (2.2)	464.7 (97.6)	417.1 (81.7)	90.0 (5.4)	12.4 (1.4)
60	6	183.4 (4.4)	556.5 (99.2)	525.9 (87.1)	94.9 (8.2)	13.7 (1.4)
90	9	275.2 (6.6)	648.2 (100.8)	635.1 (56.2)	98.8 (8.3)	14.9 (2.1)
120	12	367.0 (8.8)	740.0 (102.5)	748.1 (81.2)	101.4 (4.1)	15.8 (1.6)
150	15	458.6 (11.0)	831.7 (104.1)	881.5 (89.5)	106.6 (10.5)	16.9 (1.3)

^[a] Experimental configuration is shown in figure 2. The various mixtures of SM and PS were treated with 60 mg L⁻¹ of cationic PAM and screened. Data show phosphorus content and recovery in the separated solids. Water quality characteristics of the treated effluent are shown in table 7 and figure 3. Total P recoveries on top of the 0 mL L⁻¹ treatment are shown in figure 5. Data are means (and SD) of two replicate tests performed on three field samples ($n = 6$). Total P values are mass calculations based on 1 L of swine manure.

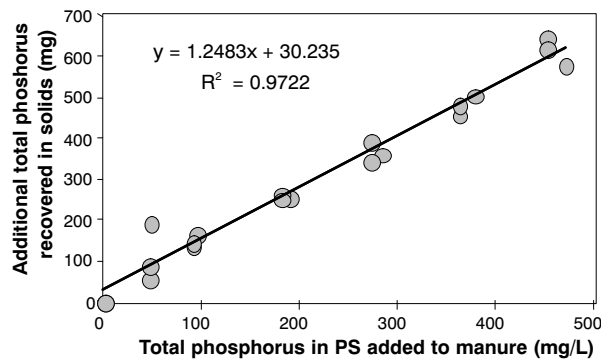


Figure 5. Total P recovered in solids separated from liquid swine manure and phosphorus sludge (PS) using PAM flocculation and screening. Data show P recovery above the amount recovered in the control without P-sludge addition (268.8 ± 81.5 mg, table 8) in duplicate tests performed separately on three field samples.

As a consequence, P content of the separated solids significantly increased, from 9.5% to 16.9% P₂O₅, corresponding to increased amounts of PS added to the manure (table 8). This higher P content in the separated solids makes the material more desirable from the point of view of its fertilizer or ash value.

CONCLUSIONS

Experiments were conducted to evaluate the feasibility of simultaneous separation of two contrasting sludges using PAM in order to simplify design of a wastewater treatment system without a lagoon and reduce its cost. The process involved the recycling of phosphorus sludge (PS) obtained in a soluble P removal unit into an homogenization tank containing raw swine manure (SM) with the goals of flocculating and dewatering the PS and SM mixture in a simultaneous operation using the same dewatering equipment and producing only one stream of solids. Results showed that this concept of simultaneous separation is technically feasible. Collectively, our findings indicate:

- The calcium phosphate precipitate generated with the soluble P removal process does not re-dissolve when mixed with SM; therefore, it is amenable for simultaneous separation with PAM.
- Although SM and PS solids have contrasting chemical characteristics, they can be efficiently (>90%)

separated using a single polymer application of cationic PAM.

- The simultaneous separation process does not increase the amount of PAM that would normally be used to effectively treat SM alone, even when the new mixture contains 43% more TSS and 94% more TP as a result of PS addition.
- Water quality (reduction of TSS, COD, TP, and TKN) of the treated liquid is improved, and the P content of the separated solids is significantly increased, which makes the material more desirable as a fertilizer.
- The simultaneous separation process of two contrasting sludges is more efficient in terms of polymer use and equipment needs compared with a situation in which two dewatering units are used to separate the same amount of solids. Thus, its implementation can help reduce installation and operational cost of the overall treatment system.

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